Injection of Radioactivities into the Forming Solar System

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ABSTRACT

Meteorite studies have revealed the presence of short-lived radioactivities in the early solar system. The current data suggests that the origin of at least some of the radioactivities requires contribution from recent nucleosynthesis at a stellar site. This sets a strict time limit on the time available for the formation of the solar system and argues for the theory of the triggered origin of the solar system. According to this scenario, the formation of our planetary system was initiated by the impact of an interstellar shock wave on a molecular cloud core. The shock wave originated from a nearby explosive stellar event and carried with it radioactivities produced in the stellar source. In addition to triggering the collapse of the molecular cloud core, the shock wave also deposited some of the freshly synthesized radioactivities into the collapsing system. The radioactivities were then incorporated into the first solar system solids, in this manner leaving a record of the event in the meteoritic material. The viability of the scenario can be investigated through numerical simulations studying the processes involved in mixing shock wave material into the collapsing system. The high-resolution calculations presented here show that injection occurs through Rayleigh-Taylor instabilities, the injection efficiency is approximately 10%, and temporal and spatial heterogeneities in the abundances of the radioactivities existed at the time of their arrival in the forming solar system.

Subject headings: hydrodynamics — shock waves — solar system: formation

1. Introduction

Studies of meteoritic material have revealed the presence of short-lived radioactivities in the early solar system (Wasserburg 1985; Cameron 1993; Podosek and Nichols 1997; Goswami and Vanhala 2000; McKeegan et al. 2000). The origin of these dozen or so confirmed (^{41}Ca, ^{26}Al, ^{60}Fe, ^{10}Be, ^{53}Mn, ^{107}Pd, ^{182}Hf, ^{129}I, and ^{244}Pu) or suspected (^{99}Tc, ^{36}Cl, ^{205}Pb, and ^{92}Nb) short-lived radionuclides has been a subject of intense investigation over the last few years. There are two basic ways to explain the production of the radioactivities: via stellar nucleosynthesis or through local production in the early solar system.

A stellar nucleosynthetic source (a supernova or an AGB star) has been the leading explanation for most of the nuclei (Cameron 1993, 2001a; Wasserburg et al. 1994, 1995, 1998). This source works well for the longer-lived radioactivities, because there is plenty of time to have them produced in stellar interiors and then mixed into the interstellar medium, including the molecular cloud core from which the solar system was formed. However, the case is more complicated for the shortest-lived radionuclides - mean life less than a few million years - since their presence sets a time limit of one million years or less for the time available between their production and their incorporation in the solar system material. This has led to the formulation of the idea of the triggered origin of the solar system (Cameron and Truran 1977; Boss 1995; Cameron et al. 1997; Vanhala 1998; Boss and Vanhala 2000), which suggests that the formation of the solar system was initiated when an interstellar shock wave propagating from a nearby explosive stellar event impacted on a molecular cloud core. In addition to triggering the collapse of the core earlier than it would have occurred otherwise, the shock wave also enriched it with freshly synthesized radioactivities produced at the stellar site and carried by the shock wave.

Another possibility for the origin of the radionuclides is to have them produced locally in the solar nebula. According to this scenario, the radionuclides were produced during spallation reactions involving energetic particles emanating from protosolar flares (Shu et al. 1997). Since the radioactivities are produced locally, there are no time constraints for the formation of the solar system, and therefore no need to connect the origin of the solar system with a nearby explosive stellar event, as long as all the detected shortest-lived radioactivities can be produced through this mechanism.

The current meteorite data suggests that the best explanation for the origin of the radioactivities requires both scenarios. Local irradiation models appear to have difficulty in matching the observed abundance ratios of the nuclides, especially that of ^{26}Al to ^{41}Ca (Srinivasan et al. 1996; Sahijpal et al. 1998; Lee et al. 1998). Even if it may be possible to overcome this problem by assuming shielding of the refractory inclusions by a less refractory mantle (Gounelle et al. 2001), local production scenarios cannot account for ^{60}Fe, and it therefore requires a stellar nucleosynthetic source (Goswami, Marhas and Sahijpal 2001). The detection of the short-lived isotope ^{10}Be in an Allende inclusion (McKeegan et al. 2000), has stirred further debate, since the nuclide is thought to be produced only by nuclear spallation reactions. Therefore, its existence has been used

to argue in favor of local irradiation scenarios (McKeegan et al. 2000; Gounelle et al. 2001), but it is unclear whether the radioactivity was produced in the solar nebula, or in an earlier phase of evolution, such as in expanding supernova envelopes (Cameron 2001b) or in the winds ejected from H-depleted Wolf-Rayet (WR) stars (Arnould et al. 2000). These considerations lead to the conclusion that a combination of stellar nucleosynthesis coupled with stellar and/or local irradiation appears to be the best explanation for the known isotopic anomalies. Indeed, there is accumulating evidence that the presence of the short-lived radioactivities in the early solar system may require a fairly involved history for their complete explanation (Meyer and Clayton 2000).

The theory of the triggered origin of the solar system therefore remains an attractive scenario to explain the presence of at least some of the short-lived radioactivities in the early solar system. In the last few years, the viability of the proposal has been investigated through numerical simulations using several different simulation methods (Boss 1995; Foster and Boss 1996, 1997; Boss and Foster 1997, 1998; Cameron et al. 1997; Vanhala and Cameron 1998; Vanhala and Boss 2000); for reviews, see Vanhala (1998) and Boss and Vanhala (2000). The simulations suggest that molecular cloud cores can be triggered into collapse by moderately slow ($\sim$10-45 km s^{-1}) shock waves (Boss 1995; Foster and Boss 1996; Cameron et al. 1997; Vanhala and Cameron 1998), and the time scale of the process, $\sim$10^5 yr (Foster and Boss 1996; Vanhala and Cameron 1998), is sufficiently short for the radioactivities to have survived in the measured amounts. Calculations studying the mixing of radioactivities into the forming solar system have shown that shock wave material can be injected into the collapsing system when the postshock gas cools rapidly, resulting in (nearly) isothermal shocks (Foster and Boss 1997; Vanhala and Cameron 1998; Vanhala and Boss 2000). In this case, shock wave material is injected into the collapsing molecular cloud core through Rayleigh-Taylor (RT) fingers, with an efficiency of 10-20% and over a time period of 700,000 years (Foster and Boss 1997; Vanhala and Boss 2000). The radioactivities can be injected into the collapsing system even if they are far behind the leading edge of the shock wave (Boss and Foster 1998). It is also possible that shock wave material can be injected into the system in non-isothermal shock waves where the postshock gas remains hot behind the shock front, but these aspects of the problem have not been investigated further because they appear to be beyond current computational power (Vanhala and Cameron 1998). Consequently, the discussion of the injection process has concentrated on the isothermal case.

Previous calculations have suggested that the abundances of the injected material may have experienced spatial and temporal variation in the early solar system. This is based on two discoveries of the interaction between the shock wave and the molecular cloud core. First, there appears be a lag of a few $\times$ 10,000 yr between the time the center of the compressed molecular cloud core is pushed into collapse and the time the radioactivities carried by the shock wave arrive deep in the system (Vanhala and Boss 2000). This is due to the fact that while the core can be pushed into collapse by the compressional wave transmitted through the core as the shock wave is decelerated by the outer layers of the core, injection becomes efficient only after the RT-fingers have developed fully at the surface of the core. This makes it possible for the amount of radioactivities to have

varied at different times within the forming solar system. Second, the calculations suggest that the RT-fingers remain well defined down to the level of a few tens of AU, making it possible for spatial heterogeneities to exist in the matter falling into different parts of the protostellar disk (Vanhala and Boss 2000). However, the resolution of the previous calculations has been insufficient to make these suggestions conclusive.

The possibility of heterogeneities in the early solar system has received support from meteorite studies. For example, the absence of evidence of live ^{26}Al in some refractory inclusions might imply their formation in the nebula just prior to the arrival of the freshly-synthesized ^{26}Al deposited by the shock wave (Sahijpal et al. 1998). It is also possible that these inclusions, as well as chondrules, which in contrast to typically ^{26}Al-enriched Ca,Al-rich inclusions (CAIs), show lower values for ^{26}Al enrichment or none at all (Hutcheon, Huss and Wasswerburg 1994; Hutcheon and Jones 1995; Russell et al. 1996; Kita et al. 2000; Huss et al. 2001), formed in nebular regions largely devoid of ^{26}Al, whereas the CAIs were formed out of ^{26}Al-rich material (MacPherson, Davis and Zinner 1995). Spatial heterogeneity is also implied by the strong evidence for a radial gradient in the distribution of ^{53}Mn in the solar nebula (Lugmair and Shukolyukov 1998). There are some arguments (MacPherson, Davis and Zinner (1995); Nichols, Podosek and Meyer (1999); see the discussion by Podosek and Cassen (1994)) that suggest that the heterogeneity may have been temporal rather than spatial, but this is currently uncertain, and more data is required.

In order to address the details of the injection process, such as the issue of the origin and longevity of heterogeneities, we have initiated a study of the interaction between the molecular cloud core and the shock wave at high spatial resolution (Vanhala and Boss 2000). The work described in this paper is the latest in a series of calculations studying the injection process under isothermal conditions. The resolution of the current study is sufficiently high to describe the behavior of the injected material at the time it arrives to the forming solar system and determine whether the heterogeneities discovered by the earlier calculations persist at this stage. The system studied in the current calculations is described in § 2, and the results of our study are given in § 3. In § 4 we summarize the results and briefly discuss their implications.

2. Simulation method and the initial system

The study presented in this paper is a continuation of the calculations of Vanhala and Boss (2000). The two-dimensional VH-1 hydrodynamics code, which is based on the piecewise-parabolic method (PPM) and includes the effect of the self-gravity of the gas, is described in greater detail by Foster and Boss (1996). Two complementary methods - a color field and tracer particles - are used to follow the behavior of the shock flow material as it impacts the molecular cloud core (Foster and Boss 1997).

The initial conditions of our calculations are the same as the standard cases of Foster and Boss (1997) and Vanhala and Boss (2000): a marginally stable Bonnor-Ebert sphere joining smoothly

to the surrounding medium. The cloud initially has a radius of 0.058 pc, temperature of 10 K, central density of $\rho_c = 6.2 \times 10^{-19}$ g cm^{-3}, and contains one solar mass of material. The intercloud medium has $T_{icm} = 10$ K and $\rho_{icm} = 3.6 \times 10^{-22}$ g cm^{-3}. The shock wave is represented by a top-hat model, in which the edge of the wave (thickness 0.003 pc) is given the velocity $v_{edge} = 20$ km s^{-1}, density $\rho_{edge} = 3.6 \times 10^{-20}$ g cm^{-3} and temperature $T_{edge} = 10$ K, while the wind behind the leading edge has $\rho_{wind} = 3.6 \times 10^{-22}$ g cm^{-3}, $T_{wind} = 10$ K and $v_{wind} = 0$ km s^{-1}. The cylindrical coordinate (r, z) grid is taken to be axisymmetric around the z axis and extends to $r = 0.088$ pc and -0.176 pc $< z <$ 0.088 pc, with the shock wave approaching from the $+z$ direction.

In accordance with the earlier studies, the wind is initially at rest. In general, the wind would be expected to have a non-zero velocity. However, we chose to keep the initial conditions the same as in previous calculations to make the calculations comparable. Also, previous calculations have indicated the the injection results do not change appreciably from the standard case with different wind velocities (Foster and Boss 1997; Boss and Foster 1998).

To further keep the current calculations comparable with previous studies, we use an isothermal equation of state, with the adiabatic index $\gamma = 1.00001$ (see discussion by Foster and Boss (1997)). Since we are interested in investigating the injection process under optimal conditions, isothermal conditions are an appropriate choice (Foster and Boss 1997; Vanhala and Cameron 1998; Vanhala and Boss 2000).

In the current calculations, the two-dimensional uniform grid has a resolution of 960 x 2880, twice the number of zones in each dimension as in the highest-resolution calculation of Vanhala and Boss (2000), and 16 times the number of zones in each dimension of the original case of Foster and Boss (1997). The size of one zone in these calculations is 19 AU (9.2×10^{-5} pc), not enough to discuss the distribution of injected material at the scale of the present-day solar system, but sufficient to describe the injection process at the time of the formation of the solar system.

3. Results

The results of our simulations are shown in FIGS. 1-3. The basic results of our calculations follow well the pattern described by Foster and Boss (1996, 1997) and Vanhala and Boss (2000). When the shock wave impacts the molecular cloud core, it is stalled at the facing side of the core, while material at the sides can sweep past the core. A compressional wave is transmitted through the core as the shock wave is decelerated by the outer layers of the cloud, and eventually the central parts of the system are pushed into collapse. At this point the Courant condition is violated due to the gravity becoming very strong and the calculation stops. The evolution of the compressed core is characterized by an initial growth spurt - about 0.5 solar masses over ~100,000 years - after which the growth of the protostellar core slows down until the final protostellar mass is reached.

While the core is being compressed by the shock wave, Rayleigh-Taylor instabilities develop at the surface of the core (FIG. 1). Shock wave material collects in clumps at the surface of the

compressed core, and RT-instabilities developing at these locations inject shocked material into the collapsing system. The complex structure of the RT-fingers is evident in FIG. 2, which shows a closeup of the last four panels of FIG. 1. The RT-fingers develop at different times at different parts of the core, according to the time at which they first come into contact with the shock wave: the facing side of the core has the instabilities develop first, while the fingers at the sides of the core are just beginning to reach deep into the system at the time the calculation stops. The injection efficiency - the amount of shock wave material captured by the collapsing system with respect to that originally incident on the molecular cloud core - is approximately 10%, the same as in previous calculations.

Our calculations show that the injection becomes efficient only after the RT-fingers have developed fully at the surface of the compressed core. Consequently, there is a lag between the time when the central regions of the core are significantly compressed and when the shock wave material arrives in the inner regions of the system. According to our calculations, this time is a few × 10,000 years. Also, the shock wave material is injected preferentially in the outer parts of the collapsing core, resulting in spatial gradients in the distribution of the radioactivities. This is evident in FIG. 3, which shows the ratio between the amount of shock wave material with respect to the total accumulated mass as a function of distance from the forming protostar. The fractional shock mass shows a clear gradient toward the outer parts of the nebula, and there are bumps in the gradient according to the clumps of matter being injected by the RT-fingers at that distance from the center of the system. These results lead us to expect that the material arrives into the forming solar system in the form of clumpy infall instead of homogeneous rain of well-mixed material. Since our calculations do not include the rotation of the core, we cannot follow the formation of the protostellar disk. Therefore, it might be possible that the arriving material would be mixed within the disk, but a preliminary study of mixing in protostellar disks suggests that heterogeneities might survive even at that stage (Boss 2001).

In addition to confirming the injection results of the previous calculations, our results also support the original conclusion of Foster and Boss (1996) and Vanhala and Cameron (1998) on the competition between the self-gravity of the core and the development of instabilities at the contact surface between the shock wave and the cloud. In the case described here and in the previous simulations of successful triggered collapse - cases of intermediate velocity shock waves striking centrally condensed molecular cloud cores - the self-gravity pulls the core to the point of collapse before the instabilities have had a chance to develop fully. At this point, the instabilities serve as feeders of shock wave material into the forming solar system instead of destroying the core, as suggested by calculations of high-velocity shock waves.

4.   Discussion

Our calculations of the impact of an interstellar shock wave on a molecular cloud core confirm the previous results: in isothermal shock waves, shock wave material is injected into the collapsing

system by Rayleigh-Taylor instabilities developing at the surface of the compressed core. Injection begins shortly after the central density of the core has started to grow due to the shock wave transmitted from the compressed outer regions of the core. The injection efficiency is $\sim$10%, and the amount of injected material in the central parts of the collapsing core is typically $\sim$0.1% of the total mass contained in that region.

Our high-resolution calculations show that the RT-fingers retain their structure down to the size of the forming solar system. We therefore expect the injected shock wave material to arrive on the disk as clumpy infall rather than as thoroughly mixed material. It is possible that instabilities might stir sufficient turbulence in the infalling gas to cause the material to be thoroughly mixed before it arrives on the disk, or that small-scale dynamically driven instabilities could occur at the surface of the RT-fingers at a scale that is beyond the resolution of our calculations. However, we do not see any evidence for this in our calculations, and our main conclusion therefore remains that the arrival of the injected shock wave material into the protostellar disk was neither spatially or temporally homogeneous. Our calculations suggest that the total number of RT-fingers reaching into the forming solar system is 10-12. If the RT-fingers remain separate on their way to the protostellar disk, the spacing between the fingers as they strike the disk depends on the size of the disk. For the 3000 AU of the panels of FIG. 2 - the size of the forming disk - the fingers would be roughly 300 AU apart, while a later-stage disk of 40 AU, for example, would see a spacing of $\sim$4 AU of the RT-fingers as they land on the disk.

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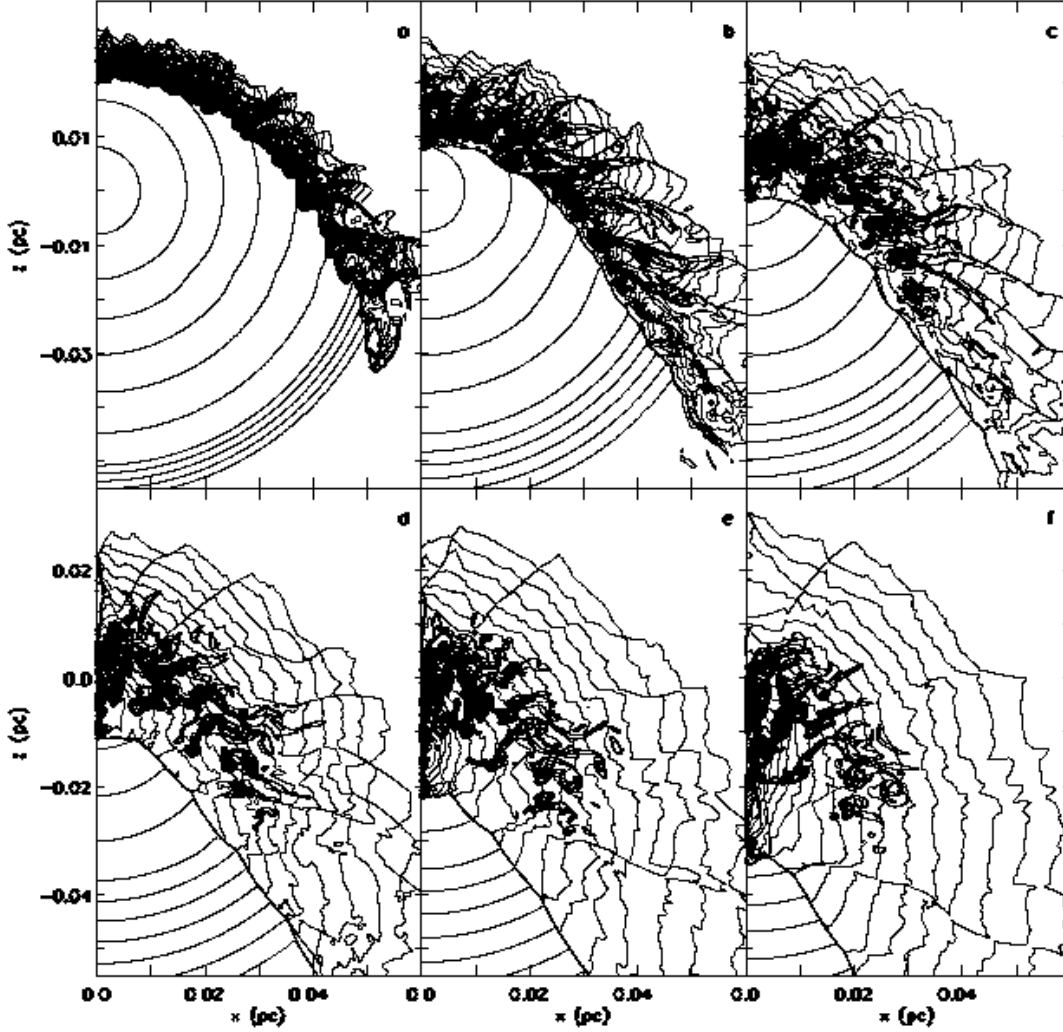
Fig. 1.— The development of Rayleigh-Taylor fingers. The system is shown at $t = 22{,}000$ yr (a), 44,000 yr (b), 66,000 yr (c), 88,000 yr (d), 110,000 yr (e), and 132,000 yr (f). The thin contours depict the gas density in the system and range from 6.20×10^{-21} g cm^{-3} (1/100 the initial central density) to 7.93×10^{-16} g cm^{-3}, with each contour representing a change of factor 1.5 in density. The thick contours show the behavior of the color field and range from 0 to 3.40×10^{-20} g cm^{-3} in steps of 2.43×10^{-21} g cm^{-3}.
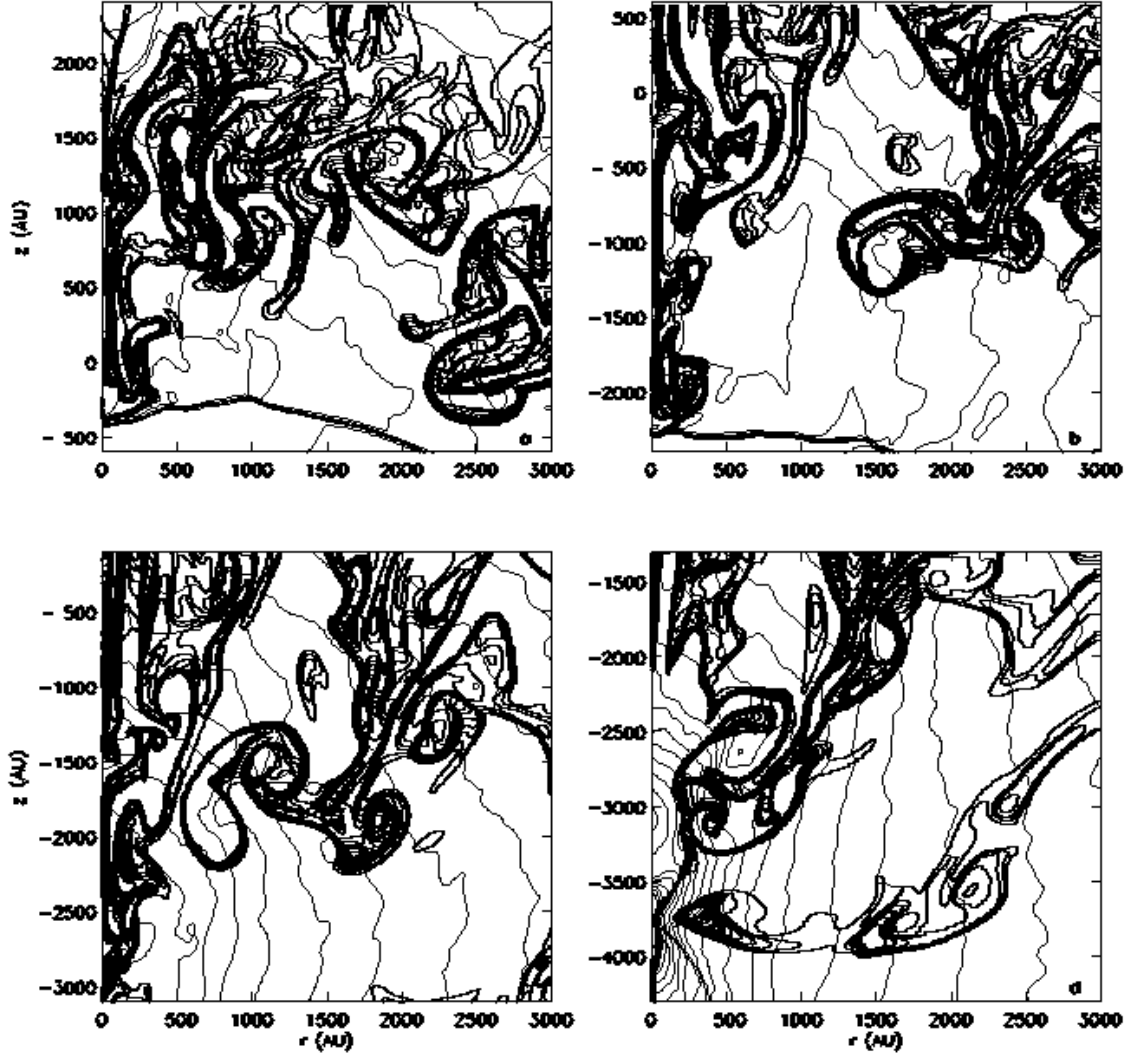
Fig. 2.— Closeup of the Rayleigh-Taylor fingers. The system is shown at $t = 66{,}000$ yr (a), 88,000 yr (b), 110,000 yr (c), and 132,000 yr (d). The thin contours depict the gas density in the system and range from 6.20×10^{-21} g cm^{-3} to 7.93×10^{-16} g cm^{-3}, with each contour representing a change of factor 1.5 in density. The thick contours show the behavior of the color field and range from 0 to 3.40×10^{-20} g cm^{-3} in steps of 2.43×10^{-21} g cm^{-3}.
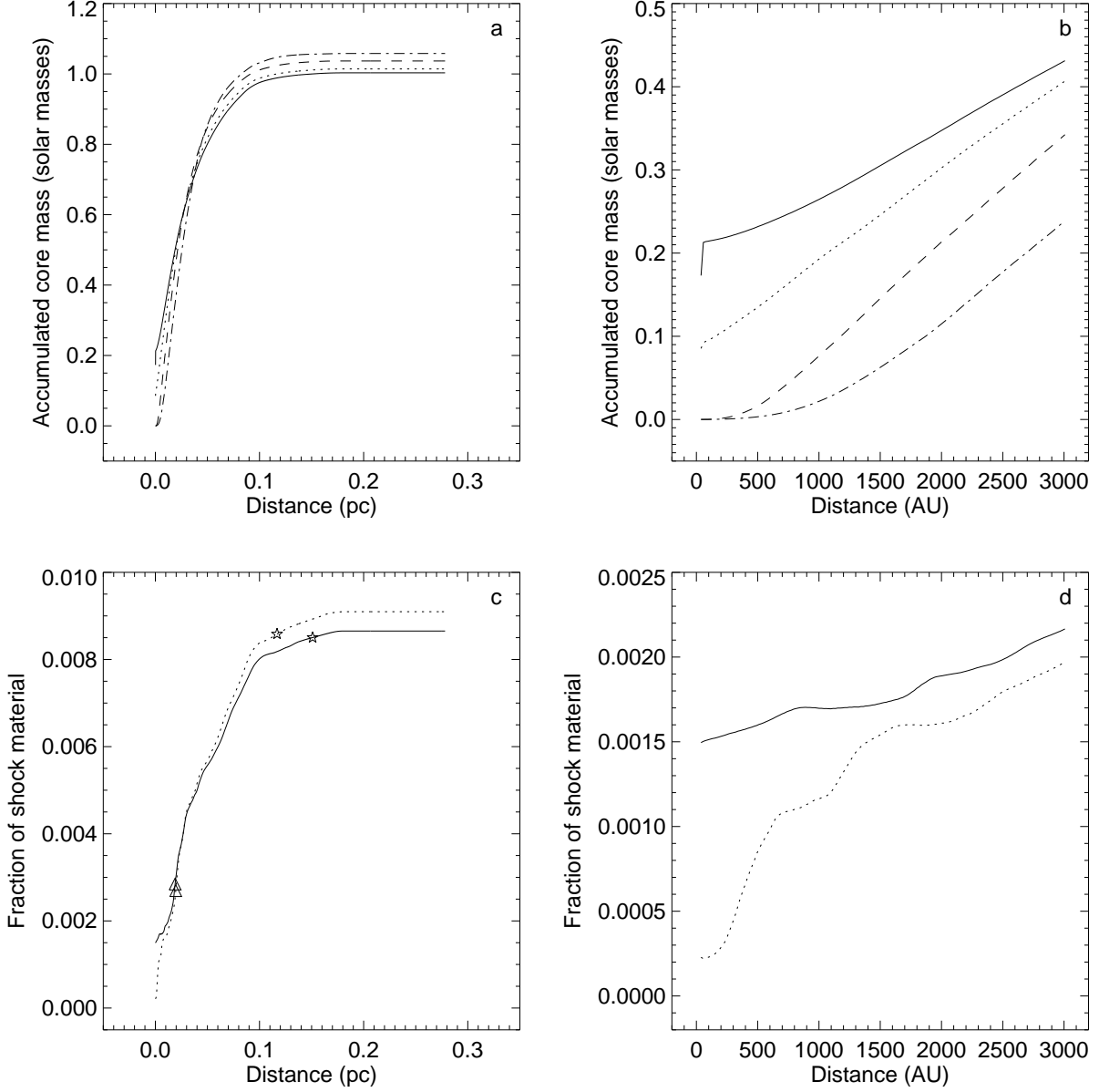
Fig. 3.— The total accumulated mass (a,b) and the fraction of the shock wave material of the accumulated mass (c,d) as a function of distance from the forming protostar. The different lines correspond to the system at $t = 88{,}000$ yr (*dashed-dotted line*), 110,000 yr (*dashed line*), 132,000 yr (*dotted line*), and 140,000 yr (*solid line*). The right-hand panels (b,d) are a closeup of the inner 3000 AU of the whole system shown in the left-hand panels (a,c). In the bottom panels, the triangle and the star correspond to the distance within which the accumulated core mass is 0.5 and 1.0 solar masses, respectively.